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Mutual Influence of the Melting Stage and Electric Arc Current Harmonic Composition in Different Types of Electric Arc Furnaces*

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Abstract: The authors of the article carried out experimental studies of the harmonic current composition of arc steel-melting furnaces of various capacities and classes operating at various metallurgical enterprises in Russia. This made it possible to carry out a comprehensive analysis of the changes in the higher current harmonics of the electric steel-making units, to identify patterns of changes in individual harmonic components, as well as to determine the average and maximum harmonic levels for arc furnaces of each type. Also, a comparative analysis was made of the change rate of the total effective values of even and odd harmonic components, which showed an important pattern in exceeding the rate of attenuation of even harmonics of an arc furnace over odd ones several times. On the basis of this, it was shown the expediency of using the rms current of even harmonics for the purpose of diagnosing the melting stages in an electric arc furnace with the classical technological process. This principle formed the basis for the structure of the new control system for the electric mode of the furnace, which implements the diagnostic technique for the melting stage according to the harmonic composition of the electric arc current signal.

Keywords: Electric arc furnace, Control system by electric mode of electric arc furnace, Electric arc, Harmonic composition of current signal in electric arc, Even harmonics, Odd harmonics, Melting stage diagnostic of electric arc furnace.

1. INTRODUCTION

Nowadays electrometallurgy is a very fast-growing sphere of modern industry. More than 50% of liquid steel is produced in electric arc furnaces (EAF) with further extra-furnace treatment in ladle furnaces (LF). It's clear that EAF is a kind of metallurgical equipment which is characterized by sufficient energy consumption. The aim of majority scientific researches in field of EAF's power control is decreasing of specific energy consumption and power-on time.

It's important to note that there are several different ways to achieve this aim. One of these ways is design and implementation of the efficient melting stage diagnostic system. Correct melting stage diagnostic allows to switch furnace transformer and reactor taps in corresponding moments according to the real technological processes inside of the furnace bath.

Nevertheless, in practice the structure of effective melting stage diagnostic system is not evident. The main problem here is choice of the correct control parameter which has a good correaltion with current condition of the scrap. Obviously, the definition of such parameter is a subject of deeper research.

2. BACKGROUND

In modern electric modes control systems (ArCOS Light, ArCOS NT, ArCOS XP, ArCOS Plus, Q-REG, A.R.C.E.L.E.C, E.M.P.E.R.E, Simelt, Melt Expert) specific power consumption $W_{SPECIFIC}$ [kWh/t] is applied as a main criterion for switching from one combination of furnace transformer and reactor tap to another. This method is classical and widespread, but it has one disadvantage. $W_{SPECIFIC}$ is a parameter which has low correlation with real processes inside of the furnace bath. This problem may led to setting of not efficient electric modes due to furnace transformer and reactor switches in wrong moments of time.

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In addition to classical method, Simelt control system has an additional option for customers and allows to set up vibration sensors on the furnace shell and use corresponding signal as a parameter for melting stage diagnostic. The efficiency of this method is confirmed by practical studies [5,6], but there is one sufficient disadvantage too. The conditions of work in steelmaking workshop are very aggressive and vibration sensor installed at the furnace shell may break down due to spilling of liquid metal or other harmful factors.

Moreover, some researchers suggest to use melting stage diagnostic methods based on neural algorithms [3,4]. In theory, neural algorithms show positive results in field of AC EAF's power control. But nowadays main developers of metallurgical equipment do not use neural algorithms in structure of their control systems. As a result, neural melting stage diagnostic system becomes unapplicable in foreseeable future.

The above stated review shows that architecture of the new melting stage diagnostic system should be designed on the base of initially available parameter, which has good correlation with processes inside of the furnace bath. In this research harmonic composition of electric arc furnace is offered as such parameter. The efficiency of this approach may be confirmed during the further analysis.

3. MAIN FEATURES OF ELECTRIC ARC PHYSICS FOR MELTING STAGE DIAGNOSTIC

In accordance with the theory of electrical arc furnaces, the presence of higher harmonics in the current chipboard due to the nonlinear current-voltage characteristic (CVC) of the electric arc. The shape of the current – voltage characteristics of the arc depends on the burning conditions that affect the intensity of the ionization and deionization processes in the arc column [5]. The most accurate method for the mathematical description of the electrical properties of an AC arc is the use of the non-linear Cassie differential equation [6], which describes the change in the instantaneous conductivity of the arc. In this equation, the key parameter is the thermal time constant of the arc θ_D, the value of which, depending on the melting stage, is in the range of θ_{ARC} = 0.3 - 5.5 ms. The lower range corresponds to the initial stage of batch liquefaction, the upper - to the stage of metal refinement, where electric arcs burn on a liquid bath.

The value θ_{ARC} affects the level of odd harmonics of a particle board. In a symmetric three-phase electrical circuit of a particle board, provided that the active resistances, inductances, mutual inductances and voltages of the electric arcs are equal, the particle board current contains only odd harmonics of three times. At current asymmetry at unequal lengths and voltage of arcs, multiples of three harmonics appear.

For the constant component and even harmonics in EAF currents, the presence of a "valve effect" [7] arises due to unequal back- electromotive force (EMF) of electric arcs when alternating the anode and cathode on the electrode and charge. In real conditions on the operating equipment, the valve effect is also the cause of the intermediate interharmonics emergence, which are caused by different forms of positive and negative half-wave current.

Figure 1 shows the results of high-speed photography of the electric-arc column at times when the cathode is an electrode and the anode is the charge (Fig. 1a), which corresponds to a positive current half-wave. The reverse situation for the negative half-wave of the current (anode - electrode, cathode - charge) is shown in Fig. 1b.

Obviously, in the first case, the arc burning is stable, and in the second case, due to the greater back-EMF of the arc, the burning process is unstable, which leads to a strong distortion of the negative half-wave current. The valve effect is most revealed in the first 5 minutes of the initial melting stage of the batch.

As an example, Fig. 2 shows the real instantaneous values of the current EAF-10 (10 MVA) for small time intervals at different stages of melting. Oscillograms in Fig. 2 corresponds to the initial stage of melting, where an unstable arc burning is observed. Here, the phenomenon of the gate effect is clearly observed: the ratio of the half-wave current amplitudes is $K_V = + I_{mEAF} / -I_{mEAF} = 780/580 = 1.35$, and even harmonics and interharmonics are present in the current (Fig. 2, b).

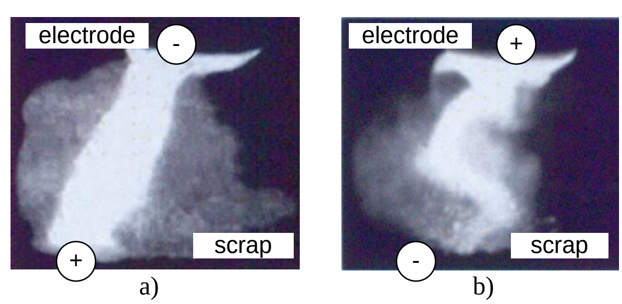

Figure1. - a visual representation of the gate effect when burning an electric arc using high-speed photography

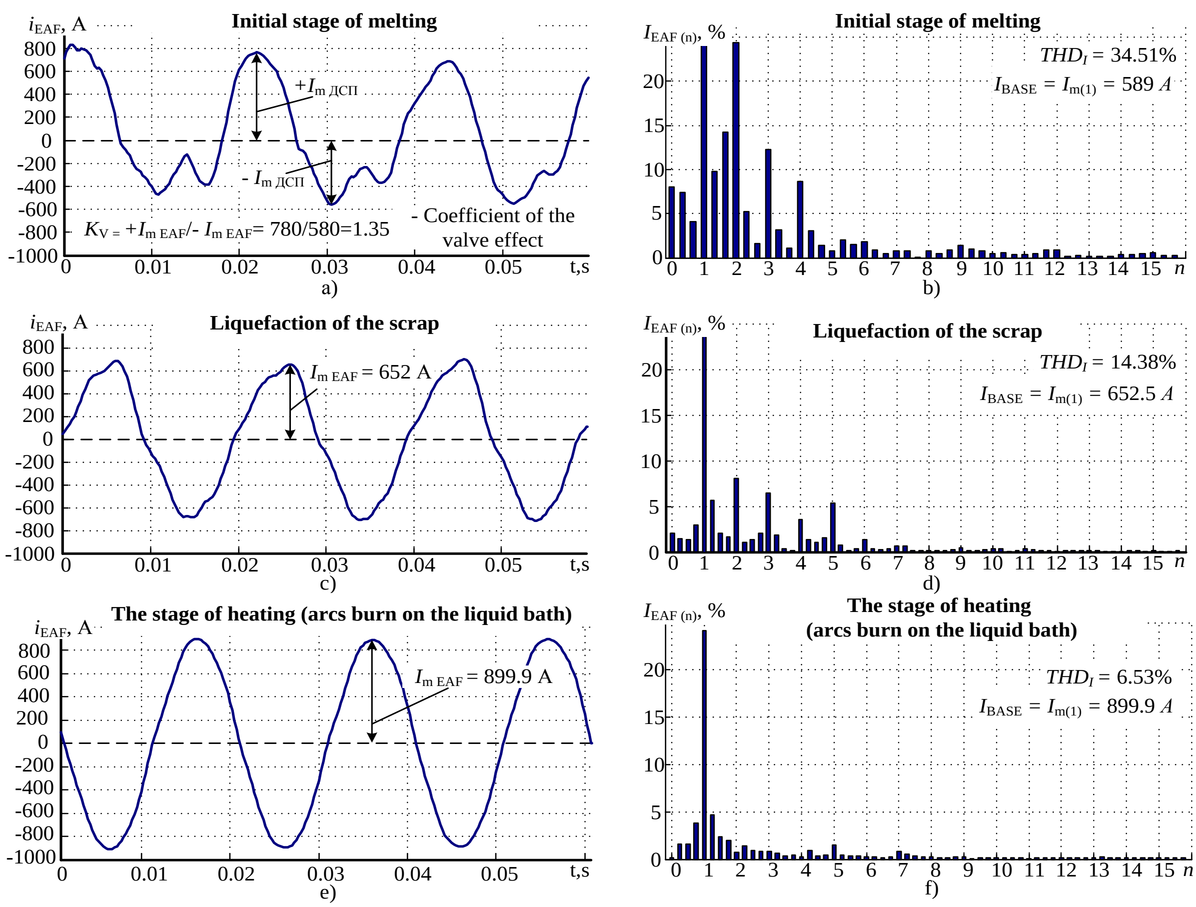

Figure 2. Harmonic composition of EAF-10 (10 MVA) currents at various melting stages

In the process of batch liquefaction, the arc burning conditions improve, which leads to a weakening of the gate effect coefficient K and an increase in the thermal constant arc θ_{ARC}, while the levels of even, odd and interharmonics decrease (Fig. 2, c and d). At the metal finishing stage, when electric arcs burn to a liquid bath, under a layer of foamed slag, the distortion of the instantaneous current form is minimal (Fig. 2, e and f). In this case, the coefficient of total current distortion K_I has the smallest value.

It should be noted that the analysis of the harmonic composition of currents on oscillograms in Fig. 2 cannot be considered complete due to the inconstancy of the levels of harmonics at certain points in time. As mentioned earlier, amplitudes in EAF vary widely, and the nature of the change is random. In accordance with this, for a qualitative analysis of the nature of the change in harmonic components, it is necessary to construct temporal dependencies by harmonics for the entire melting cycle in a EAF or a metal working cycle in a LF, depending on the furnace characteristics. As part of this work, the studies were conducted on furnace units, the main characteristics of which are summarized in Table 1.

Thus, the connection between the harmonic composition of the electric arc current signal and the θ_{ARC} value, and therefore the stage of melting of the batch, is obvious. As a consequence, the task of applying the analysis of the harmonic composition of an electric arc current signal to diagnose the melting stage of a batch in a EAF as part of an electric mode control system is of particular relevance.

Note that to date, the vast majority of modern control systems for the electric mode of the furnace [8] as a parameter responsible for switching from one combination of furnace transformer stage, reactor and operating curve number uses the specific power consumption signal $W_{SPECIFIC}$ [kWh / t]. At the same time, W_{spe} is not a parameter that directly reflects the real processes occurring inside the furnace bath, which causes the most significant drawback of this method for determining the melting stage of the batch.

TABLE I. ELECTRICAL SPECIFICATIONS AND PARAMETERS OF THE POWER SUPPLY SYSTEMS OF THE INVESTIGATED ELECTRIC STEEL-MAKING UNITS

Name of parameter	Type of electric steel unit					
	Shaft melting furnace SF -120 t., CJSC "Severstal - Mill Plant Balakovo "	Shaft melting furnace SF -120 t., CherMK PJSC Severstal	Electric arc furnace EAF-120 tons. PJSC "Ashinsky Metzavod"	Electric arc furnace EAF-10 OOO «BVK»	Electric arc furnace EAF - 1,5 т. OOO «SUMVZ»	Ladle Furnace LF 180 t. ESPTS OJSC MMK
1. Transformer rated voltage S_N, MVA	85	85	90	10	1,25	26
2. Rated primary voltage $U_{L.N}$, kV	35	35	35	10	6	110
3. Measuring range of secondary voltage U_2, kV	0.67 – 1,15	0.67 – 1.15	0.65-1.00	0.2-0.38	0.103-0.225	0.29 – 0.37
4. Rated primary current I_{1N}, A	1109-1402	1109-1402	1123-1485	577.4	120.3	136.5
5. Rated secondary current I_{2N}, kA	42.7-57.9	42.7-57.9	52.0-60.5	15.2	3.21	35.7-40.5
6. Nominal reactor power $Q_{R.N.}$, MVAr	8,8	8,8	Not applicable	1,8	Not applicable	Not applicable
7. Mean power of short circuit at transformer connection point S_{SC}, MVA	750	838	919	179	52,4	3300
8. Parameters of AF (amplification factor) in power supply system EAF (LF)	SVC 135 MVAr	Not applicable	SVC 100 MVAr	Power correction device with harmonic filtering 6,3 MVAr	Not applicable	Not applicable

4. EXPERIMANTAL INVESTIGATION OF THE CHANGES IN HARMONIC COMPOSITION OF CURRENTS DURING THE MELT CYCLE IN DIFFERENT ELECTRIC ARC FURNACES

Table 2 shows the results of statistical signal processing, containing information on the values of harmonics [9, 10] and equivalent parameters at the main stages of melting of various electric steel-making units, which served as part of this work. The instantaneous values of the currents and phase voltages were recorded using a multichannel recorder of electrical signals with a high sampling rate of 4,000 Hz. In this case, in accordance with Kotelnikov’s theorem, the maximum recognizable frequency in the signal spectrum is 2000 Hz (40th harmonic). Studies conducted earlier showed that the maximum number of significant harmonics of EAF and LF does not exceed n = 11, therefore the frequency range under study for even and odd components was adopted from 0 to 550 Hz. The actual values of all higher harmonics $I_{HH}.\Sigma$ and the total current distortion coefficient KI were calculated without limiting the frequency range at the maximum sampling rate.

In the study of harmonics changes in time, relative parameters were introduced for the convenience of analysis ($I'_{HH.\Sigma}$, $I'_{HH\cdot EVEN}.\Sigma$, $I'_{HH\cdot ODD}.\Sigma$, $I'_{IH}.\Sigma$, $I'_{(0)}$ - $I'_{(11)}$), reduced to the base value - the nominal value of the primary current of the furnace transformer I_H. In contrast to the coefficients of the n- harmonic components of the current, calculated relative to the 1st harmonic [11, 12], the use of these parameters makes it possible to avoid a strong increase in the relative level of harmonics at times when phase arises breaks arcs or discontinuous current modes. In this case, the presence of interference in the measured signal would have a significant impact due to the small value of the first harmonic current. Below are the expressions used to calculate the listed relative parameters.

1. The relative effective value of the total current of higher harmonics:

$$I'_{HH.\Sigma} = \frac{\sqrt{I^2_{EAF} - I^2_{EAF(1)} - I^2_{EAF(0)}}}{I_N} \cdot 100\%, \quad (1)$$

where I_{EAF} is the current (RMS) of EAF (LF), measured on the basis of the instantaneous value of arc furnace current; $I_{EAF\ (1)}$ - the effective value of the first harmonic of the EAF current (LF); $I_{EAF(0)}$ - constant component of chipboard current (LF); I_N is the rated current of a EAF transformer (LF).

2. The relative effective value of the total current of even harmonics:

$$I'_{\text{HH.EVEN.}\Sigma} = \frac{\sqrt{I^2_{\text{EAF(0)}} + I^2_{\text{EAF(2)}} + I^2_{\text{EAF(4)}} + I^2_{\text{EAF(6)}} + I^2_{\text{EAF(8)}} + I^2_{\text{EAF(10)}}}}{I_{\text{N}}} \cdot 100\% \quad (2)$$

where $I_{\text{EAF (2)}}$, $I_{\text{EAF (4)}}$, $I_{\text{EAF (6)}}$, $I_{\text{EAF (8)}}$, $I_{\text{EAF (10)}}$ are the actual values of significant EAF even harmonics.

3. The relative effective value of the total current of odd harmonics:

$$I'_{\text{HH.ODD.}\Sigma} = \frac{\sqrt{I^2_{\text{EAF(3)}} + I^2_{\text{EAF(5)}} + I^2_{\text{EAF(7)}} + I^2_{\text{EAF(9)}} + I^2_{\text{EAF(11)}}}}{I_{\text{N}}} \cdot 100\% \quad (3)$$

where $I_{\text{EAF (3)}}$, $I_{\text{EAF (5)}}$, $I_{\text{EAF (7)}}$, $I_{\text{EAF (9)}}$, $I_{\text{EAF (11)}}$ are the effective values of significant EAF odd harmonics.

4. The relative effective value of interharmonics and unaccounted harmonics above the 11th:

$$I'_{\text{IN.}\Sigma} = \frac{\sqrt{I^2_{\text{EAF}} - I^2_{\text{HH.EVEN.}\Sigma} - I^2_{\text{HH.ODD.}\Sigma}}}{I_N} \cdot 100\% . \quad (4)$$

5. The coefficient of the total current distortion of the arc furnace was determined by the well-known formula as the ratio of the total effective value of the higher current harmonics to the effective value of the current of the first harmonic:

$$THD_I = \frac{I_{\text{HH.}\Sigma}}{I_{\text{EAF(1)}}} \cdot 100\% = \frac{\sqrt{I^2_{\text{EAF}} - I^2_{\text{EAF(1)}} - I^2_{\text{EAF(0)}}}}{I_{\text{EAF(1)}}} \cdot 100\% , \quad (5)$$

6. The relative effective values of the n-harmonics were determined as follows:

$$I'_{(n)} = \frac{I_{\text{EAF(n)}}}{I_{\text{N}}} \cdot 100\% , \quad (6)$$

where $I_{\text{ДСП(n)}}$ is the effective value of the n- harmonic, determined using the Fourier transform of the instantaneous value of the EAF (LF) current [13,14].

It should be noted that the listed parameters were calculated individually for each phase of the EAF with the subsequent finding of the arithmetic average value. The parameters were calculated in the Matlab-Simulink environment based on arrays of instantaneous currents [15–16]. In order to prevent incorrect bursts of the average K_I coefficient at the time of switching on the furnace transformers and when the EAF operates on two arcs, a logic circuit was developed analysing the phase-by-phase consumption of the full power of the arc furnace at each calculation step.

As an example in Fig. 3 shows the graphs of the change in the harmonic components of the current of the shaft steel-making furnace SF-120 (120 tons, 85 MVA) of CJSC "Severstal - Mill Plant Balakovo" for one melting cycle. For a visual display of the main stages of smelting, a graph of changes in the power of the shaft furnace S_{SF} (t) was also constructed (Fig. 3, a), on which the studied time intervals are marked: TI1 is the stage of charge melting; TI2 - the stage of finishing the metal with burning arcs on a liquid bath.

Also it is important to note that all parameters were initially calculated at 20 ms intervals. After that, using the moving average algorithm, we obtained smoothed curves, reflecting the character of changes in the averaged values of the harmonic components. The time constant of the averaging block was chosen different. In order to display the graphs, the value T1 = 30 s was used, and the value T2 = 3 s was used for statistical signal processing in order to find the maximum and average harmonic levels.

It should be mentioned that the identified features of changes in harmonic components at SF-120 (85 MVA) of CJSC "Severstal - Mill Plant Balakovo" are also valid for the rest of the studied EAF with the traditional technology of melting (Table 1). An exception is the EAF with a continuous conveyor feed of the charge into the liquid bath (Consteel, Danieli) and the installation of the EAF, where the arc most of the time of melting work on a liquid bath under a layer of slag. In this case, the levels of harmonics depend on the regimes of slag formation and the intensity of the purging of the liquid stage with argon. In some cases, at the EAF during periods of smelting, where the intensity of metal blowing is increased, the harmonic plots may have an increasing character.

Based on the analysis of the graphs of the harmonic components of the current of a powerful EAF, it can be concluded that the $I'_{\text{HH.EVEN.}\Sigma}$ parameter correlates well with the technological stages of melting. This parameter can be used to build advanced control systems for electrical chipboard modes, in which, instead of the specific consumption of electrical energy W_{SPEC}, information is used on the higher harmonics of the arc currents. The $I'_{\text{HH.EVEN.}\Sigma}$ parameter is preferable to determine the end of the charge melting period compared to the other coefficients since it has the best correlation with the conditions of electric arc burning [17,18].

TABLE II. HARMONICS COMPOSITION OF THE EAF AND LF CURRENTS AT DIFFERENT HEAT STAGES

Type and parameters of the electric steel-making unit	Investigated period of heat		Information about high harmonics of the EAF (LF) current supplied from the feeder line														
			Even harmonics						Odd harmonics					Equivalent parameter			
			$I'_{(0)}$, %	$I'_{(2)}$, %	$I'_{(4)}$, %	$I'_{(6)}$, %	$I'_{(8)}$, %	$I'_{(10)}$, %	$I'_{(3)}$, %	$I'_{(5)}$, %	$I'_{(7)}$, %	$I'_{(9)}$, %	$I'_{(11)}$, %	I'_{HH}, %	$I'_{HH.H}$, %	$I'_{HH.Ч}$, %	K_I, %
1. Shaft furnace SF-125 (85 MVA). CJSC Severstal – Long Product Mill Balakovo (Balakovo, Russia). Charge material – 100% scrap. $U_{L.N}$ = 35 kV, $\boldsymbol{I_N}$ **= 1402 A.**	Initial stage of batch material melting	Average	3.3	5.0	2.8	1.8	1.2	1.0	5.8	3.3	3.9	1.2	1.0	12.4	8.5	7.8	11.9
		Max.	13.3	15.0	7.2	3.9	2.7	2.3	10.9	5.9	5.6	2.8	1.9	25.2	13.7	22.4	33.9
	Arcs burning on the liquid bath	Average	1.4	2.7	2.0	1.5	0.9	0.8	3.6	1.8	3.7	1.0	0.9	8.2	6.0	4.4	6.7
		Max.	2.8	4.0	3.4	2.6	1.5	1.4	6.5	2.6	4.9	1.9	1.8	10.4	8.4	5.6	8.8
	The whole melt cycle	Average	2.1	3.6	2.3	1.6	1.0	0.9	4.7	2.6	3.8	1.1	0.9	10.1	7.2	5.8	9.1
		Max.	13.3	15.0	7.2	3.9	2.7	2.3	10.9	5.9	5.6	2.8	2.1	25.2	13.7	22.4	33.9
2. Shaft furnace SF-130 (85 MVA). CherMK PJSC Severstal (Cherepovets, Russia). Makes use of 30% of liquid iron. $U_{L.N}$ = 35 kV, $\boldsymbol{I_N}$ **= 1402 A.**	Initial stage of batch material melting	Average	2.3	2.6	1.2	0.7	0.5	0.4	4.5	2.5	1.0	0.5	0.4	7.4	5.6	4.1	8.7
		Max.	13.9	11.6	5.6	3.0	2.3	1.6	14.5	4.9	3.1	1.9	1.4	24.6	16.1	19.2	28.3
	Arcs burning on the liquid bath.	Average	1.6	1.8	0.9	0.6	0.5	0.4	3.0	3.2	1.2	0.5	0.4	6.0	4.9	2.9	6.8
		Max.	5.5	7.4	2.5	1.5	1.2	0.9	7.3	4.6	2.1	1.3	1.0	11.9	8.3	9.3	8.5
	The whole melt cycle	Average	1.8	2.1	1.0	0.6	0.5	0.4	4.0	2.3	0.9	0.4	0.3	6.4	5.1	3.3	7.4
		Max.	13.9	11.6	5.6	3.0	2.4	1.8	14.5	4.9	3.1	1.9	1.9	24.6	16.1	19.2	28.3
3. Electric arc steel-making furnace EAF-120 (90 MVA) (Asha, Russia) PJSC Asha metallurgical plant. $U_{L.N}$ = 35 kV, $\boldsymbol{I_N}$ **= 1485 A.**	Making use of conventional technology (initial stage)	Average	6.3	5.9	2.5	1.4	1.0	0.7	6.0	2.2	1.3	0.9	0.7	12.9	6.9	10.0	16.7
		Max.	16.1	12.3	5.0	3.6	2.2	1.7	10.9	4.9	2.6	1.7	1.5	21.8	12.0	20.2	32.9
	Making use of Consteel technology (whole cycle)	Average	0.7	1.1	0.5	0.3	0.2	0.2	4.1	1.4	0.6	0.7	0.3	5.0	4.6	1.5	5.1
		Max.	4.1	6.3	2.2	1.0	0.9	0.8	6.2	3.2	1.7	1.3	0.9	10.7	6.9	8.5	14.9
4. Electric arc steel-making furnace EAF-10 (10 MVA), BVK ltd. (Chelyabinsk, Russia) $U_{L.N}$ = 10 kV, $\boldsymbol{I_N}$ **= 577.4 A.**	Initial stage of batch material melting	Average	5.7	6.9	2.8	1.5	0.9	0.7	5.9	2.6	1.3	0.9	0.6	13.2	6.9	10.5	16.9
		Max.	23.2	16.7	5.5	3.4	2.3	1.7	12.4	5.7	2.6	2.1	1.5	32.6	14.0	30.3	31.1
	Arcs burning on the liquid bath	Average	1.1	1.5	0.7	0.4	0.3	0.2	1.9	2.1	0.9	0.3	0.3	4.1	3.2	2.3	4.6
		Max.	5.6	5.6	2.4	1.2	0.9	0.6	5.6	3.9	1.8	0.9	0.7	11.1	6.6	8.3	14.9
	The whole melt cycle	Average	3.1	4.0	1.6	0.9	0.6	0.4	4.1	2.8	1.3	0.6	0.5	8.6	5.5	5.9	10.8
		Max.	23.2	17.2	6.6	3.4	2.3	1.7	12.4	5.7	2.8	2.3	1.6	32.6	14.0	30.3	36.2
5. Electric arc steel-making furnace EAF-1.5 (1.25 MVA), SUMVZ ltd. (Staroutkinsk, Russia) $U_{L.N}$ = 6 kV, $\boldsymbol{I_H}$ **= 120.3 A.**	Initial stage of batch material melting	Average	15.0	21.0	7.2	3.5	2.2	1.6	13.8	6.4	2.8	1.9	1.9	35.0	16.5	29.4	24.0
		Max.	36.1	40.5	15.3	8.0	5.1	4.2	28.5	12.6	6.0	5.2	4.7	65.3	32.3	59.8	42.0
	Arcs burning on the liquid bath	Average	2.6	4.6	1.4	0.5	0.3	0.2	2.6	3.1	1.0	0.3	1.3	7.6	4.6	5.8	5.8
		Max.	14.5	13.6	5.9	3.1	1.9	1.7	12.6	6.4	2.2	1.8	2.4	27.1	15.0	21.3	15.9
	The whole melt cycle	Average	5.7	8.3	2.8	1.3	0.8	0.6	5.9	4.1	1.5	0.8	1.3	14.5	8.0	11.4	10.9
		Max.	36.1	40.5	15.3	8.0	5.1	4.2	28.5	12.6	6.0	5.2	4.7	65.3	32.3	59.8	42.0
6. Ladle furnace LF 180 t. (26 MVA) OJSC MMK (Magnitogorsk, Russia) $U_{L.N}$ = 110 kV, $\boldsymbol{I_N}$ **= 136.5 A.**	Heating of liquid bath within the whole cycle	Average	0.8	1.1	0.5	0.3	0.2	0.1	1.3	0.6	0.3	0.2	0.1	2.4	1.6	1.6	3.4
		Max.	21.8	28.8	10.7	4.8	2.9	2.5	17.1	7.8	4.2	3.5	2.9	42.2	20.3	39.6	15.6

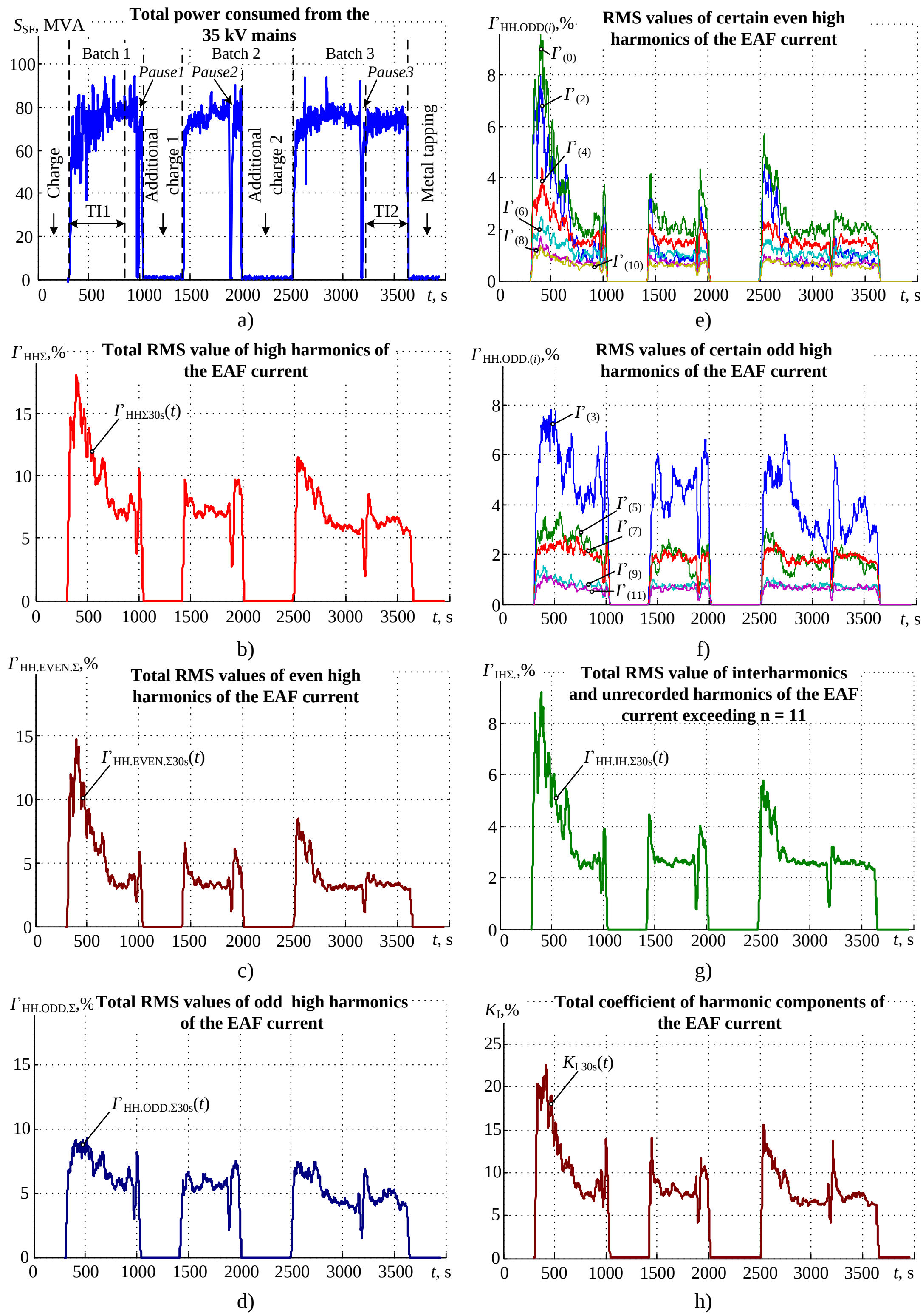

Figure 3. Changes in the harmonic components of the current of a Shaft melting furnace SF-120 (120 t., 85 MBA) CJSC "Severstal - Mill Plant Balakovo " for one melting cycle

5. Construction of the control system with the electrical mode of EAF taking into account the peculiarities of changing the harmonic composition of the electric arc current during melting

In order to confirm the conclusion made in the previous section, we analysed the rate of change of the relative effective values of the currents of even and odd harmonics $I'_{HH.EVEN \cdot \Sigma}$ (t) and $I'_{HH.ODD \cdot \Sigma}$ (t) on the initial hundred - melting of charge (the first 10 minutes of work under current). As can be seen from the figure, the average attenuation rate of even harmonics A1 = $dI'_{HH.EVEN \cdot \Sigma}$ (t) / dt is -0,0162% I_N / s, which is four times higher than A2 = $dI'_{HH.ODD \cdot \Sigma}$ (t) / dt for odd harmonics (Figure 4). The rates of change of the effective values of $I'_{HH.EVEN \cdot \Sigma}$ (t) and $I'_{HH.ODD \cdot \Sigma}$ (t) were approximately determined using first-order regression models. At the same time, the smoothed curve $I'_{HH.ODD \cdot \Sigma}$ (t) has a better correlation with the thermal time constant of the arc, which can also be used for various problems of controlling electric modes [19–20], for example, to determine the level of foamed slag or diagnostics of the state of the technological process at later stages of melting, when the levels of even harmonics are minimal and practically do not change.

The above-mentioned feature of the change in the harmonic composition of the electric arc current signal is used in a fundamentally new system for controlling the electrical regime of a EAF, which was developed and patented by the authors of the article (RF patent for useful model No. 176106) [21]. The functional diagram of this system is presented in Figure 5.

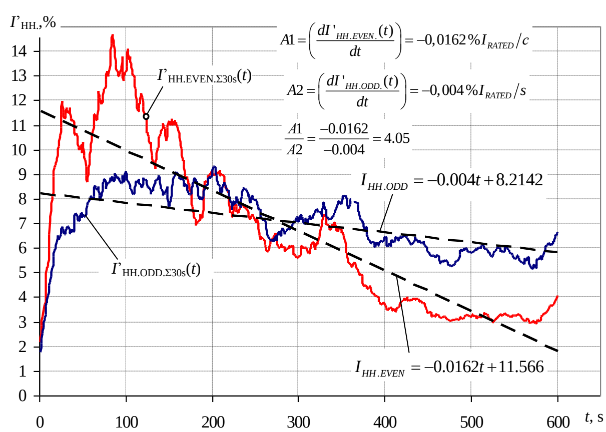

Figure 4. Comparative analysis of the change rate of the relative effective values of the currents of even and odd harmonics of the shaft furnace at the Incipient state of batch liquefaction (the first 10 minutes of work under current)

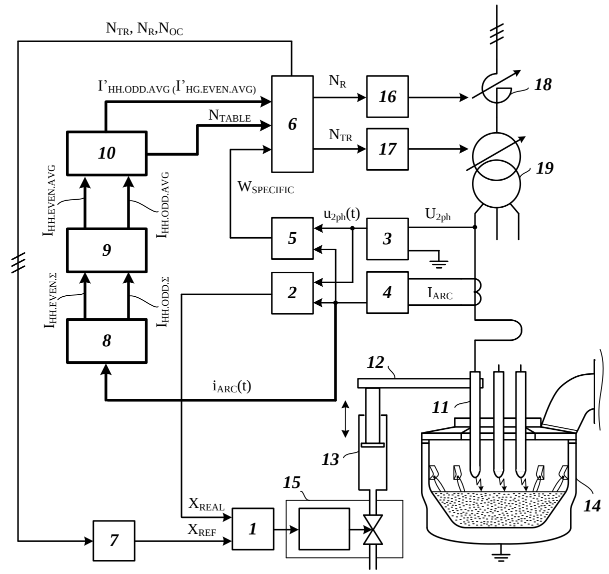

Figure 5. Block diagram of the new control system of the EAF electric mode (the Russian Federation utility patent No 176106): 1 – control module of the first level; 2 – calculation module of the control parameter; 3 – phase voltage sensor; 4 – electric arc current sensor; 5 – calculation module of specific energy consumption; 6 – control module of the second level; 7 – matrix of preset control parameters; 8 – calculation block; 9 – averaging module; 10 – mode selection module; 11 – electrode; 12 – electrode arm; 13 –hydraulic cylinder; 14 – furnace bath; 15 – servo valve; 16 – on-load tap changer of the reactor; 17 – on-load tap changer of the transformer; 18 – reactor; 19 - transformer).

Thus, the novelty of this control system is that as a criterion for the transition from one combination of furnace transformer stage, reactor and operating curve number to another, at the initial stage of melting, the signal $I'_{HH.EVEN \cdot \Sigma}$ (t) is used, and in later stages of melting - $I'_{HH.ODD \cdot \Sigma}$ (t) [22]. The implementation of this principle is achieved by applying in the structure of the system the units of calculation and averaging 8 and 9, respectively, with the help of which the direct calculation of the signals $I'_{HH.EVEN \cdot \Sigma}$ (t) and $I'_{HH.ODD \cdot \Sigma}$ (t), as well as block mode selection 10, which is responsible for the formation of the electric mode of furnace operation and the selection of the melting profile table.

It should be noted that the melting profile in this case differs from the classical one and consists of two tables (tables 3-4). In one table, which is used at the initial stage of melting, the values of $I'_{HH.EVEN \cdot \Sigma}$ (t) are indicated, upon reaching which the transition to another combination of N_{TR}, N_R и N_{OC} is made. The second table is similar in its structure to the first one, but it indicates the values for $I'_{HH.ODD \cdot \Sigma}$ (t), and it is used in the later stages of melting. At the same time, the transition from one table to another is carried out if within one minute the value of $I'_{HH.EVEN \cdot \Sigma}$ (t) changes by no more than 10%.

6. EXPERIMENTAL SETUP

The above-stated control system structure for testing was implemented on the operating facility in a simplified form. Thus, as a criterion for the transition from one combination of the furnace transformer stage, reactor, and the number of the working curve, only the $I'_{HH.EVEN\cdot\Sigma}$ (t) parameter was used. Based on the analysis of a sample of more than 100 heats, the boundary values of $I'_{HH.EVEN\cdot\Sigma}$ (t) were determined for each of the three baskets (Fig. 7).

TABLE III. HARMONICS COMPOSITION OF THE EAF AND LF CURRENTS AT DIFFERENT HEAT STAGES

Step	Value of $I'_{HH.EVEN.AVG}$	N_{TR}	N_R	N_{OC}
1	$I'_{HH.EVEN.CR1}$	N_{TR1}	N_{R1}	N_{OC1}
2	$I'_{HH.EVEN.CR2}$	N_{TR2}	N_{R2}	N_{OC2}
3	$I'_{HH.EVEN.CR3}$	N_{TR3}	N_{R3}	N_{OC3}
…	…	…	…	…
n	$I'_{HH.EVEN.CRn}$	N_{TRn}	N_{Rn}	N_{OCn}

TABLE IV. HARMONICS COMPOSITION OF THE EAF AND LF CURRENTS AT DIFFERENT HEAT STAGES

Step	Value of $I'_{HH.ODD.AVG}$	N_{TR}	N_R	N_{OC}
1	$I'_{HH.ODD.CR1}$	N_{TR1}	N_{R1}	N_{OC1}
2	$I'_{HH.ODD.CR2}$	N_{TR2}	N_{R2}	N_{OC2}
3	$I'_{HH.ODD.CR3}$	N_{TR3}	N_{R3}	N_{OC3}
…	…	…	…	…
n	$I'_{HH.ODD.CRn}$	N_{TRn}	N_{Rn}	N_{OCn}

The results of the first level control system on SF-125 (85 MVA), in which the melting profile was laid, shown in Fig. 7 shown in Fig.8. This control system provides switching of the N_{TR}, N_R and N_{OC} when the control parameter $I_{HH.EVEN.\Sigma}$ achieves preset profile values. Each operating curve (from 1 to 3) corresponds to short, medium and long arc respectievly. It's important to notify that the structure of melting profile in fig. 8 is flexible and may be corrected according to the certain type of equipment.

The resulting analysis showed that the use of the system for diagnosing the batch liquefaction makes it possible to reduce the specific energy consumption by approximately 1.5% within the framework of selective melting. At the same time, a set of statistics is being conducted to substantiate the economic effect of the implementation of the measures mentioned above.

New structure of the melting stage profile based on levels of current harmonics

N_{BUCKET}	*Stage*	$I'_{HH.EVEN.\Sigma}$,%	N_{TR}	N_{OC}	N_R
1	*1.1*	>12%	6	1 Short arc	3
	1.2	≤12% & ≥5%	10	3 Long arc	3
	1.3	≤5%	9	2 Medium arc	3
2	*2.1*	>4%	6	1 Short arc	3
	2.2	≤4%	9	2 Medium arc	3
3	*3.1*	>7%	6	1 Short arc	3
	3.2	≤7% & >3%	9	2 Medium arc	3
	3.3	≤3%	8	1 Short arc	3

Figure 7. The structure of the experimentally implemented melting profile

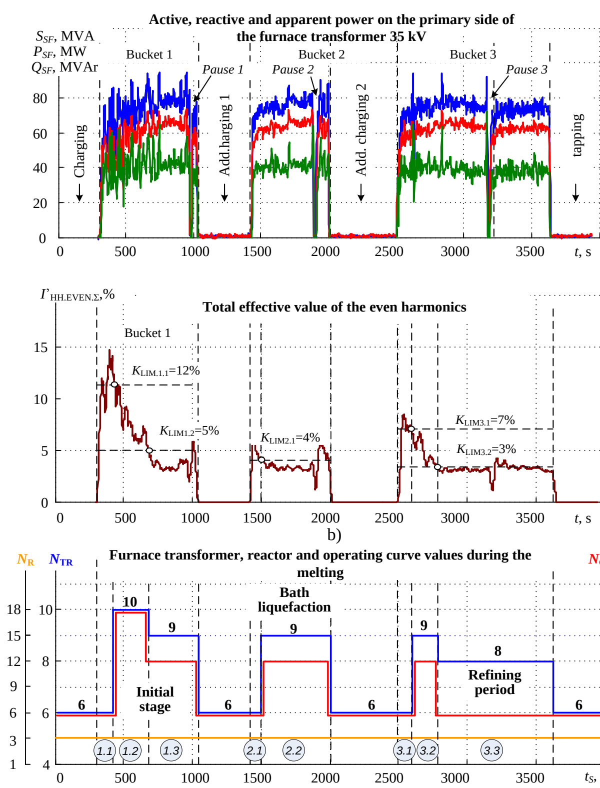

Figure 8. - experimental graphs of the electric mode control system of EAF with a system for diagnosing the melting stage according to the highest harmonics of the arc current

7. CONCLUSIONS

1. In the majority of modern control systems with the electrical regime of EAF, the value of the specific energy consumption $W_{SPECIFIC}$ [kWh / t] is used as a criterion used to determine the current stage of melting. At the same time, this parameter allows only indirectly judging the actual processes occurring inside the furnace bath, as a result of which the batch liquefaction stage is not determined accurately and the transition from one combination of the furnace to the transformer, reactor and the number of the working curve to another is out of time. This leads to a non-optimal electrical operation of the furnace and a decrease in technical and economic indicators of the quality of the steel-melting complex.

2. As an alternative to W_{SPEC}, the analysis of the harmonic composition of the electric arc current signal can be used to diagnose the batch liquefaction. A similar approach is due to the physical properties of the electric arc: as the melting proceeds, the thermal constant of the arc time θ_D changes in a range of 0.3 - 5.5 ms, as a result of which the waveform of the instantaneous value of the arc current approaches the sinusoidal and the proportion of harmonic components in its composition is reduced.

3. Experimental evaluation of the harmonic composition of the arc current signal carried out on electro-technological units of different power showed that the signal $I'_{HH.EVEN \cdot \Sigma}$ (t) is the most preferable indicator of the current stage of batch liquefaction at the initial stage, and the signal $I'_{HH.ODD \cdot \Sigma}$ (t) - at the melting end, when the value of $I'_{HH.EVEN \cdot \Sigma}$ (t) remains almost unchanged for a long period of time.

4. The revealed regularities of changes in the harmonic composition of the electric arc current made it possible to develop a fundamentally new system for controlling the electrical mode of EAF (RF patent for utility model No. 176106), in the structure of which a special unit for calculating the signals $I'_{HH.ODD \cdot \Sigma}$ (t) and I 'is used. $I'_{HH.EVEN \cdot \Sigma}$ (t), on the basis of which the formation of the electric mode of the furnace is made. The use of a new control system provides a more accurate determination of the stage of batch liquefaction, as a result of which a reduction in the specific energy consumption, operating time under current, as well as the total duration of melting is achieved, which has a positive effect on the performance of the steel-melting complex.

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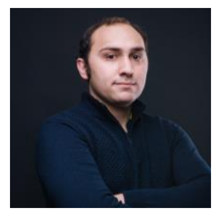

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